High-Speed Magnetic Rotor with HTS Bearings for Precision Energy Losses Investigation

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***Abstract*—We investigated physical mechanisms for flux pinning and energy losses due to inter- and intragrain flux motion by the high-accuracy experimental technique that uses the levitation effect. Low-power self-stabilizing magnetic rotors with HTS bearings have been designed on the basis of obtained results. Its rotation speed may be up to 200,000 r.p.m. The low energy consumption of the rotor enabled us to determine the energy losses in any sample in alternating magnetic field with an accuracy down to 10^{-11} W. By this method we investigated magnetic flux dynamics in Y-123 and Bi-2223 granular superconducting samples and determined that flux motion in a Y-123 sample is described by intragranular thermally assisted flux flow with viscosity equal $8 \cdot 10^{-5}$ kg/m·sec. We have also studied the frequency dependencies of energy losses for rotors with non-ideal magnetic symmetry and found the optimization criterion for rotor designing.**

I. Introduction

Of the large scale HTS applications which are actively evolving today, the systems with passive levitation have attracted the most attention [1], [2]. In this work on the one hand we investigate some parameters of high speed magnetic rotors [3] determined by the macroscopic magnetic properties of the HTS bearings. On the other hand we have shown that such rotors can be used as a precision device for direct investigations of energy losses in magnetic materials in alternating magnetic fields.

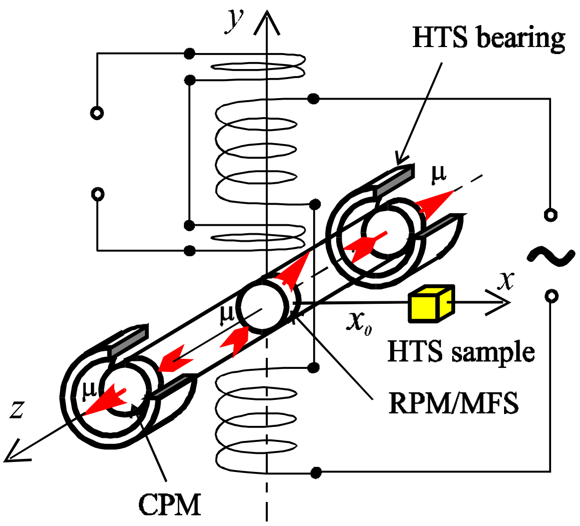

Fig. 1. Horizontal configuration of rotor for energy loss measuring.

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II. Experimental Technique

We use a configuration where a freely rotating permanent magnet (RPM) is a part of the rotor which is levitated in superconducting stator by means of carrying permanent magnets (CPM). The field from the CPM, in ideal case, is symmetric about the rotational axis. In such a configuration, the energy losses of the rotor are mainly determined by air friction. We have achieved 200 000 rpm in a vacuum of only 10^{-2} Torr at a power consumption ~ 7 mW. It makes this rotor a very sensitive and useful tool for energy loss measurements.

Fig. 1 presents the device for energy loss investigations with a horizontal positioning of the rotor. It is 50 mm in length and 7 mm in diameter. Its mass is 1.5 g. Such a rotor was described in detail in our previous work [3]. In this case the RPM is both a magnetic drive and an a.c. magnetic field source (MFS) for investigated samples [4]. We used the system of two a.c. coils for driving the rotation and two small coils as the inductive detector.

We determined the consumed rotor power from the formula

$$P = \pi \mu H_0 \omega |\cos\phi| , \qquad (1)$$

where ϕ is the phase difference between driving and detector coils voltages; H_0 is the magnetic field amplitude induced by the driving coils; and μ is the magnetic moment of the driving magnet [3].

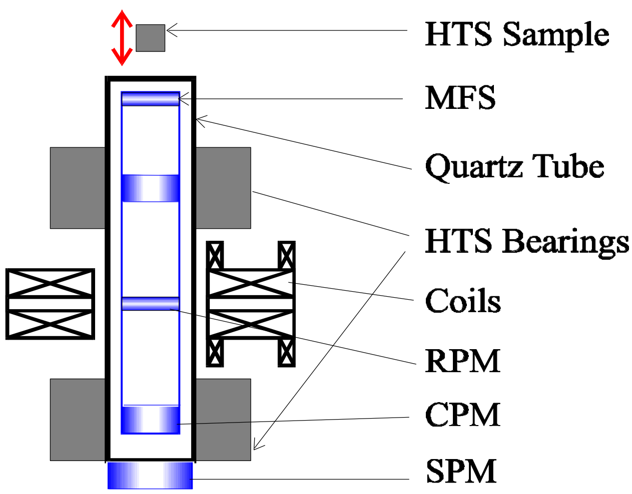

Fig. 2. Vertical configuration of rotor.

Fig. 2 presents the advanced construction with vertical positioning of the rotor and use of a supporting permanent magnet (SPM) which provides an opportunity to increase the weight of the rotor and use the additional magnet as a source of magnetic field. In this case the pure rotational component of the magnetic field in the vicinity of the investigated sample can be realized.

III. Background and Optimization

A. Resonance Oscillations Technique

The main rotor optimization parameter is the energy loss in the HTS bearings due to magnetic flux motion. Various non-ideal rotors (with different field amplitudes h generated in the HTS bearings at rotation) show the predicted behavior that we derived from the resonance oscillations technique [5]–[9]. This technique uses the simple experimental configuration (Fig. 3) where a small permanent magnet (PM) levitates above a superconducting sample. The forced oscillations of the PM were excited by the a.c. coil located above the magnet so that vectors of coil's magnetic field and its gradients over the PM area do not coincide with the x, y, z axes in Fig. 3. For a more detailed description see [5] or [8].

There are five modes s of PM oscillations in the PM—HTS system: three translation modes, $s = x, y, z$ (along the corresponding axes); and two rotation (or torsion) modes, $s = \psi$ and θ (around x and y axes respectively). Every mode has the following parameters of its own: a resonance frequency ω, damping δ, and their dependencies on the PM amplitude A. All of these parameters give us information about the magnetic flux dynamics in the HTS volume.

From the resonance frequencies ω_s we have determined

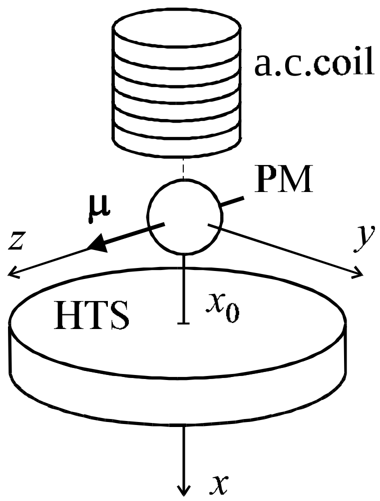

Fig. 3. Experimental configuration in resonance oscillations technique.

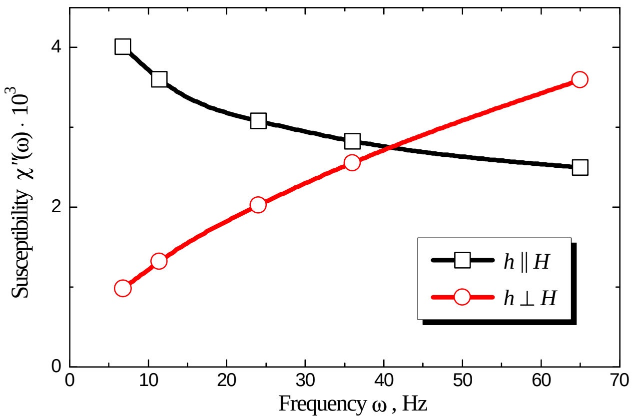

Fig. 4. Imaginary part of susceptibility vs alternating magnetic field frequency for longitudinal and transverse field components for Y-123 HTS.

the superconducting grains' volume fraction α and given information about the equilibrium magnetization of the HTS volume [5]. These parameters can be described by the following equation for every s mode

$$G_s \omega_s^2 = \alpha(\xi_s + \beta\zeta_s)\frac{\mu^2}{x_0^5}\ , \tag{2}$$

where $G_x = G_y = G_z = m$ is the PM mass, $G_\psi = G_\theta = J$ is the PM inertial moment, μ is the PM magnetic moment, x_0 is the distance to the HTS surface, β is the factor describing the contribution of the HTS volume magnetization, ξ_s and ζ_s are geometrical coefficients derived from analytical integrating in [3].

In the papers [5] and [6] we have also shown that levitation properties (elasticity and damping) are determined by magnetization properties of individual grains rather than intergrain currents [2].

From the damping factors, the frequency dependencies of the energy loss $W^*(\omega)$ for longitudinal and transverse components (index * corresponds to the symbol ∥ and ⊥ respectively) of an alternating magnetic field were obtained [7], [9]

$$W_s^* = 4\pi^2\alpha\mu^2 x_0^{-5}\xi_s^*\chi_*''(\omega)A^2 . \tag{3}$$

Here A is the PM amplitude [9]. The exact values of the geometrical coefficients ξ_s^* are given in [7]. The dependencies of the imaginary part of the susceptibility $\chi''(\omega)$ are presented in Fig. 4.

As the analysis has shown, the longitudinal component of an alternating magnetic field in the HTS volume is mainly realized for x and y modes (see Fig. 3) but at other modes the main contribution to the energy loss is from the transverse component [9].

We have observed a distinct crossover from $\delta(A) = \text{const}$ to sharp increasing of δ for Y-sample. This crossover takes place when the amplitude of alternating magnetic field on the HTS surface $h = h_c \sim 12$ Oe [6]–[8]. At this amplitude thermally assisted flux flow (TAFF) transforms to flux creep

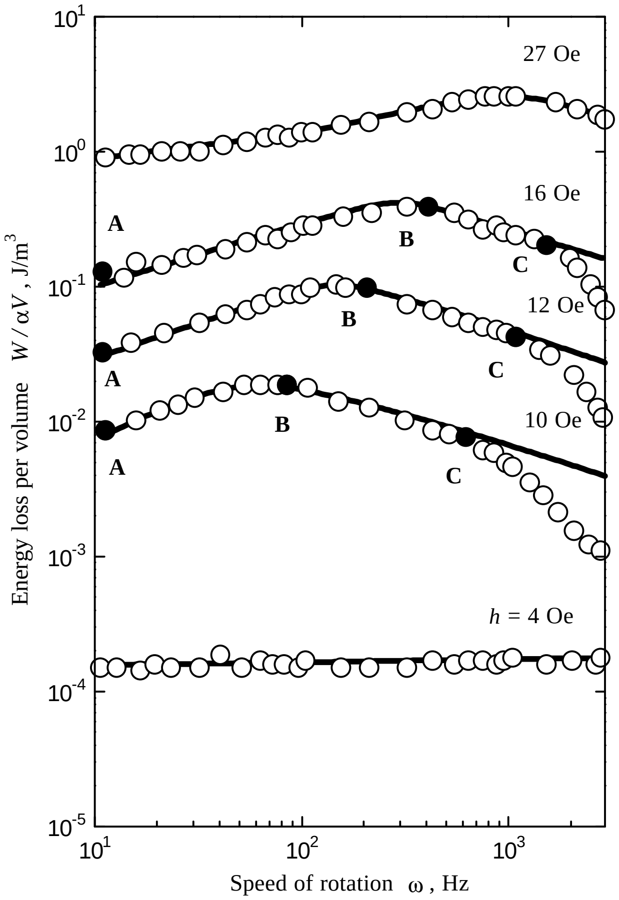

Fig. 5. Energy losses per volume of the HTS sample vs rotor's speed for the different field amplitude that depend on distance between HTS sample and rotor.

(FC) and flux flow (FF) [10]. It is the transition from viscous to hysteretic energy losses [7]–[9].

B. Rotor's Optimization

All of the above results are very important for a rotor's optimization. For very non-ideal rotors with a.c. field induced in the HTS bearings $h >> h_c$ we observed the considerable hysteretic energy losses that are frequency independent ($W(\omega)$ = const or power consumption is proportional to rotating speed). But for slightly non-ideal rotors with $h < h_c$ the energy losses are much less and depend on the type of non-ideality, i.e. the position and direction of CPM magnetic moments.

When CPM moments are placed in parallel with the inertial axis of the rotor, the longitudinal component of a.c. field is mainly generated (same as *x* and *y* modes of PM oscillations on Fig. 3). Such losses, as it follows from Fig. 4, decrease with the speed of rotation and do not make a noticeable contribution to the rotor's energy consumption at higher frequencies.

If the CPM moments make some angle with the inertial axis, a transverse alternating magnetic field component is induced in the HTS bearings when these rotate. It is the same as for ψ and θ rotation oscillations modes. In this case the energy loss increases with frequency and reaches a peak at ~10^3 Hz [3].

The self oscillations of the rotating rotor along and across the inertial axis induce different components of a.c. fields in the HTS bearings, but their resonance frequencies are in the range from 5 to 30 Hz depending on the rotor's configuration. In this range the energy losses are sensible resulting in a damping of the rotor's oscillations.

From the above we can conclude that even slightly non-ideal rotors with magnetic moments in the supporting magnets of the HTS bearings which are parallel to the inertial axis have very low magnetic losses at high speed rotation and have good damping of low frequency self oscillations when Y-123 ceramic or composite samples are used as HTS bearings.

IV. Rotor as Instrument

The low power consumption of the rotor (its rotation *Q*-factor is ~ 10^6) gives us an opportunity to use it as a precision instrument for energy loss measuring in magnetic materials in the presence of an alternating magnetic field. We can measure the attenuation of the rotation speed to get the dependence of the energy loss on field frequency [3], but for a more precise investigation, we measured the phase difference (1). The accuracy of the method in this case is determined by the measurement accuracy of current in the a.c. coil and the phase difference and can resolve 10^{-11} W.

Fig. 5 shows the frequency dependencies of the energy loss in an yttrium HTS sample obtained in the horizontal configuration of the rotor (Fig. 1) with the phase difference method [4]. From the **A** to **C** points these dependencies are in a good agrement with the model of critical state with a strong viscosity [4]. The peak positions of these dependencies (in the **B** points) correspond to "full penetration" of the alternating magnetic field in the superconducting grains and from [10] we can get the value of the linear viscosity

$$h = \frac{1}{2}\frac{\phi_0\, b}{D^2\, \omega_p} \approx 10^{-4}\,\frac{\text{kg}}{\text{m sec}} \qquad (4)$$

where ϕ_0 is the magnetic flux quantum, *b* is the alternating magnetic field amplitude, *D* is the diameter of superconducting grains, ω_p is the peak frequency in Hz.

This viscosity describes the intragrain flux motion by TAFF mechanism [9] with a characteristic time of flux diffusion τ ~ 10^{-3} sec. The viscosity associated with flux diffusion into HTS grains (for a longitudinal alternating magnetic field) is much larger than intragrain viscosity [7], [9]. It can be explained by a strong surface pinning. We did not observe a peak for this field component but we have determined the value of the characteristic time $\tau \sim 1$ sec from another levitation technique where the PM moves through the aperture of a granular HTS sample under gravity with a constant velocity [11].

For the Bi-2223 sample, the pattern is complicated significantly by noticeable intergranular losses [6], but we can speak of a significant pinning at the grains' surface (although it is much weaker than in the Y-sample).

V. Conclusions

The macroscopic magnetic properties of granular Y-123 used in HTS bearings provide some useful features for rotor construction. These include rapid damping of low frequency transverse and longitudinal rotor vibrations and, at the same time, very low energy losses even for non-ideal rotors with magnetic moments parallel to the inertial axis.

We have shown that the described rotor is a precision device for direct investigation of energy losses in magnetic materials in the presence of alternating magnetic fields.

We have found a peak in the relationship of the energy loss vs rotational magnetic field frequency and determined the value of intragranular flux motion viscosity for Y-123 HTS.

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